ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES,
ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

Contribution to
the “Italy in Japan 2011” initiative
Science, Technology and Innovation

ACCIDENT AT FUKUSHIMA DAI-ICHI NPP: DESCRIPTION AND FIRST SAFETY-RELATED CONSIDERATIONS

F. De Rosa, M. Di Giuli, G. Grasso, P. Meloni, S. Monti,
M. Polidori, F. Rocchi, M. Sangiorgi, F. Troiani, K. Voukelatou[1]

Abstract

In March 11th 2011 a huge earthquake stroke the Pacific coast of Japan, causing the automatic shut-down of 14 Nuclear Reactors. In addition, Fukushima Dai-ichi nuclear power plant was hit by a devastating tsunami wave. The engineered safety systems were not able to prevent a severe accident. This document is a first attempt to describe the early accident phase and to make focus on some relevant safety issues.

Keywords

Fukushima NPP, BWR, Safety, Nuclear accident, Accident Management.

Introduction

In March 11th 2011 the worst earthquake and tsunami registered in Japan’s recent history stroke its Eastern coast, causing the loss of over 20,000 lives and up to $300 billion in damages. Nuclear power plants, among all other industrial facilities, were those mostly affected by the two combined events: eleven nuclear reactors automatically shut down, eight of them reached safe conditions, but in the Fukushima Dai-ichi plant three reactors suffered a severe accident.

Since the very beginning of the accident, people working at ENEA, Reactors Safety Technical Unit, started gathering information, analyzing the accident causes and estimating the consequences over the population and the environment. In fact, the accident at the Fukushima Dai-ichi nuclear power plant generated worldwide public concern inducing also some governments to review their nuclear energy policies. Nowadays, in many countries, the general perception is that nuclear energy is not safe enough, but the conclusions to be drawn are, in our view, rather different.

In this paper we will try to explain:

1. Accidents dynamics
2. Public health impact
3. Lessons learnt and Issues raised

Accidents dynamics

At the time of the earthquake, in Japan there were 54 nuclear power reactors in operation: 20 Pressurized Water Reactors and 34 Boiling Water Reactors. Moreover, 3 reactors were under construction and 11 planned to be built. Japan is ranked as the third country with nuclear power installed in the world. The electricity produced by its fleet contributed around 30% to domestic total demand.

Fukushima Dai-ichi reactors were all BWRs, units 1, 2 and 3 were in operation and units 4, 5 and 6 were under periodic inspection. When the 9.0 magnitude earthquake stroke Japan, all reactors, for safety reasons, shut down automatically, electrical grid connection was lost and the emergency AC Diesel generators started. The situation was extremely tough but still under control.

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[1] ENEA, Technical Unit for Reactor Safety and Fuel Cycle Methods.

Soon after, a 14 m high tsunami wave hit the plant (design wave was 5.7 m) and the emergency generators failed as well. The loss of offsite power (due to the earthquake) and onsite AC power (due to the tsunami) combined with the rapid discharge of the DC batteries provoked a complete station blackout and, subsequently, loss of ultimate heat sink.
The station blackout disabled the Emergency Core Cooling System (ECCS), made it difficult to monitor critical parameters[2] and to open critical safety valves[3] which, in turn, led to fuel and containment overheating and damage.

Under these conditions, it was not possible to recover in time the emergency cooling systems and, as a consequence, a partial core-melt occurred in all three reactors, causing the release of radioactive material and hydrogen. The containment buildings prevented these dangerous materials to spread out to the environment, but the venting maneuvers and hydrogen explosions put a strain on containments integrity.

Table 1 – Fukushima Dai-ichi nuclear reactors

Unit	*Type*	*First criticality*	*Electric power*
Fukushima I – 1	BWR-3	October 1970	460 MW
Fukushima I – 2	BWR-4	July 18, 1974	784 MW
Fukushima I – 3	BWR-4	March 27, 1976	784 MW
Fukushima I – 4	BWR-4	October 12, 1978	784 MW
Fukushima I – 5	BWR-4	April 18, 1978	784 MW
Fukushima I – 6	BWR-5	October 24, 1979	1,100 MW

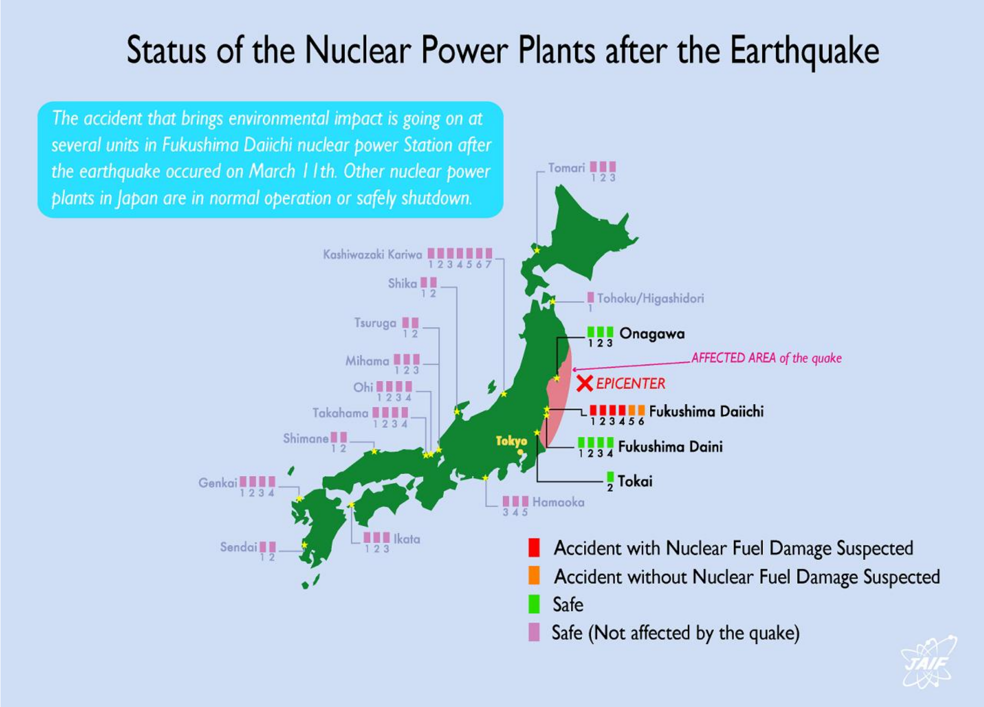

Fig. 1 – Status of the Nuclear Power Plants after the Earthquake

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[2] Reactor water level.

[3] Safety/relief valves, isolation condenser return valves, containment vent valves.

Consequently, there was a significant radioactive release to the environment and to the sea. The accidents have been finally declared INES 7 for Units 1, 2 and 3 and INES 4 for Unit 4. It took several weeks before keeping the situation under full control, limiting the releases and keeping cooled the reactors. Cold shut down (cooling water temperature < 100°C) is foreseen to be achieved by the end of 2011.

Public health impact

Radioactivity release from the plant has been large and some workers received significant radiation doses (>100 mSv whole-body equivalent), but health risks for them and the population in general are expected to be negligible. In fact, no loss of life happened or is expected as a consequence of the accident.

Direct damage and casualties inflicted on Japan by the earthquake and tsunami exceed largely any other damage caused by the accident at the nuclear power plant.

The Level 7 on the INES nuclear event scale (worst level), in which Fukushima accident has been classified, indicates an “accident with large release of radioactivity accompanied by widespread health and environmental effects”. Even though Chernobyl had been rated at the same level, the two accidents are strongly different. Fukushima released about 10% radioactivity than Chernobyl, thanks to the presence of a containment building, and the radionuclides released in the vicinity of the NPP are mostly iodine and cesium isotopes whilst in Chernobyl the entire core inventory was spread out to the environment, even far away from the NPP. Moreover, the physical form of the releases in Fukushima are mostly aqueous whilst in Chernobyl were mostly volatile. In addition, favorable weather conditions wiped away the release from the site to the sea and a prompt population evacuation resulted in vastly smaller overall consequences.

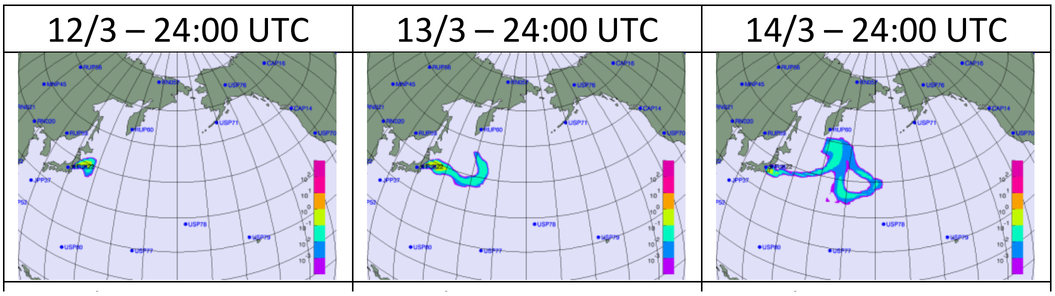

Fig. 2 - Release from the site to the sea

Now the Japanese authorities are trying to keep the cumulative radiation doses to the public below 20 mSv in the first year following the reactor accident, acting on three points:

1. monitoring radiation on food and water
2. indoors sheltering in areas where cumulative dose-rates over one year are expected to be > 10 mSv
3. relocation of residents from within a 20 km radius zone around the plant

Doses to people living far from the Dai-ichi plant are much lower. Even if the present scientific knowledge is not able to assure that 20 mSv over 1 year result in measureable harm, this dose value is usually assumed as a conservative threshold to estimate the radiation risk at low doses.
Using the linear extrapolation model, it has been estimated that 10 cancers could appear if 100 people received a single dose of 1 Sv. Lower doses result in lower risk proportionally.

Thus, a dose of 20 mSv (considering it as an acute impact) gives:

20 mSv x 10% cancer probability / 1 Sv = 0.2% cancer probability

In other words, the 20 mSv dose represents a 0.2 % chance of being diagnosed with cancer later in life, in addition to a 42 % risk which anybody faces due to common unavoidable causes.

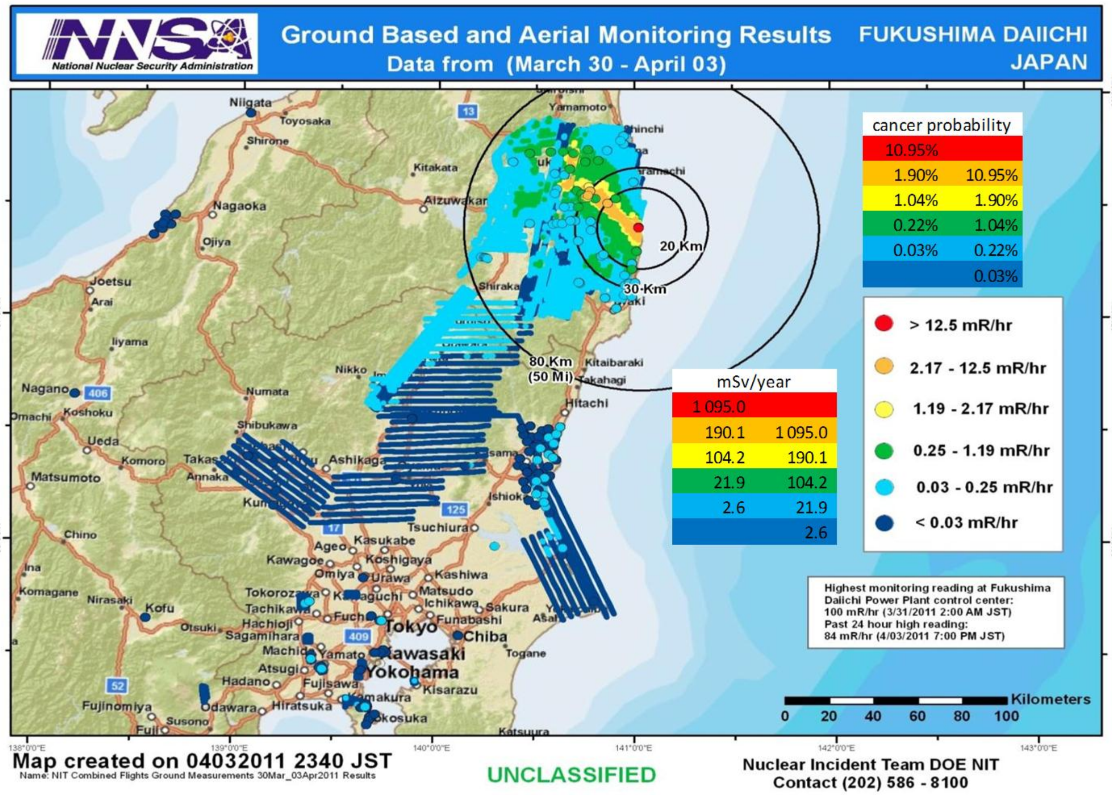

Fig. 3 – Radioactivity release from the plant

Lessons learnt and Issues raised

Fukushima accidents drew the attention of the nuclear sector on the following main issues:

- Emergency Power supply following Beyond Design Basis Accidents
  The loss of total AC power led to core degradation. This issue was already known, but it was considered under control. In old plants the solution to this

issue consisted in housing at least an AC generator in a water-proof place (not always possible) and assuring in reasonable time a transportable generator (in Fukushima, the magnitude of the natural disaster made this operation impossible). Modern nuclear power plants have solved this issue by design (not by patches as in older plants) implementing a mix of passive and active safety systems.

- <u>Emergency Response to Beyond Design Basis Accidents</u>

  The public opinion is that the response to the accident was not adequate, but this is a misleading position. The evacuation was prompt but possibly too conservative in comparison to the magnitude of the release and not selective regarding the people age. Even the communication of radiation levels to the public was confused. These are still open issues that the regulatory authorities and the scientific community are called to solve.

- <u>Hydrogen Management</u>

  Hydrogen explosions are a major issue since the first studies on core degradation. Fukushima Dai-ichi units were equipped to deal with hydrogen: the building containments were inerted with nitrogen and a venting system was available. Nevertheless, these provisions were not sufficient to avoid explosions. Moreover, venting is a controlled release to the environment and should be avoided by design. Analogous plants in the USA have a hardened venting system. Other plant designs assume passive autocatalytic recombiners as technique to mitigate the hydrogen release. Some other modern plants use small igniters. Anyway, since the main cause of hydrogen production is the Zircalloy oxidation of the fuel cladding, a broad discussion is being opened in the international nuclear community on the possibility to use alternative cladding materials (SS, SiC, etc.). It means that further studies on this topic are needed.

- <u>Containment Integrity</u>

  Since venting is a controlled release to the environment, it struggles against the design philosophy that the containment is the ultimate barrier to prevent radioactive releases to the environment and thus it should be avoided by design. Hydrogen explosions have also affected the containment integrity, with leakage inside the reactor building. Modern reactors introduced the concept of passive containment cooling, thus eliminating the need for venting as a mean to reduce the containment pressure when AC power is not available.

- <u>Spent Fuel Pools integrity and coolability</u>

  The loss of spent fuel pool cooling rose in the first weeks after the accident considerable concern because it could trigger potential pool damage. The way of protecting and maintaining cooled the spent fuel is still an open issue. Old pools could be retrofitted with passive cooling systems. The time in which the spent fuel stays in the pool should be as small as possible and the fuel should be stored far away from the reactor. Dry fuel storage should be used when possible.

- Plant Siting and Site Layout

  From this respect the lesson learned from Fukushima accident is pretty clear: one single external event affected all units on the same plant causing an accident for each of them simultaneously. How many units should be allowed on the same site? Should the actual sites be reviewed for extended and combined external events? The current siting criteria should be revised keeping in mind Fukushima and assuring more independence of regulatory bodies from the government and industry needing.

- General considerations
  Defence in depth requirement has to be reviewed for redundancy, diversity and physical separation of multiple barriers, as well as independence for severe accident management provisions. Capability of the NPPs to withstand extended loss of all electrical power as well as prolonged loss of ultimate heat sink should be improved. Finally, enhancement of essential supplies, including alternative sources of power (e.g. mobile generators shared among different NPPs and located at regional level) and effective on-site and off-site accident management strategies should be part of the provisions of any NPP to face extreme external hazards.

Conclusions

As a result of many expert meetings, held worldwide, the following topics have been selected and suggested as relevant to be solved:

1. Containment venting.
2. Effectiveness of sustained spent fuel cooling in case of accident including the understanding of the effect of spent fuel pool water leakage.
3. Phenomenology and conditions promoting oxidation of spent fuel.
4. Modelling capabilities of Boiling Water Reactor systems, like IC (Isolation Condenser) and RCIC (Reactor Core Isolation Cooling);
5. Development of methodologies for the analysis of common mode failures and cumulative accidents.
6. Robust and reliable instrumentation able to operate in severe accident conditions.
7. Management of hydrogen risk, including simulation.
8. Assessment of the predictive capabilities of fission product behaviour (transport, core and spent fuel pool).

To make more valuable all topics mentioned above, a general review of barriers characterizing all nuclear power plants should be performed, further investigating the general safety approach that takes into account design extension conditions to nuclear safety in term of strengthening the defence in depth concept.